AFOSR-TR-97

0270

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REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
18 Sep 96

3. REPORT TYPE AND DATES COVERED
Final Technical Report 1 Dec 92 to 30 Nov 95

4. TITLE AND SUBTITLE
Unsteady Aerodynamic and Heat Transfer Studies in a Highly-Loaded Transonic Turbine Rotor Cascade with Simulated Shock/Wake Passing

5. FUNDING NUMBERS
f49620-93-1-0047

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
110 Duncan Avenue, Suite B 115
Bolling AFB, DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The objective of the research effort is to integrate fluid and heat transfer studies in a heated transonic turbine cascade in order to develop a better understanding of the complex flow physics involved in the coupling of the fluid flow and heat transfer phenomena in an unsteady flowfield. To that end detailed, time-resolved aerodynamic and heat transfer measurements are taken in the experiments. Unsteady passing shock is generated in a shock tube and introduced into the tes section of the cascade to simulate the shock wave passage similar to an actual turbine environment.

14. SUBJECT TERMS

15. NUMBER OF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

Final Report

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Grant Number

F49620-93-1-0047

Grant Title

Unsteady Aerodynamic and Heat Transfer Studies in a Highly-Loaded Transonic Turbine Rotor Cascade with Simulated Shock/Wake Passing

Funding Period

Dec 1 1992 - Nov 30 1995

August 1996

I. Objectives

The objective of the research effort is to integrate fluid and heat transfer studies in a heated transonic turbine cascade in order to develop a better understanding of the complex flow physics involved in the coupling of the fluid flow and heat transfer phenomena in an unsteady flowfield. To that end detailed, time-resolved aerodynamic and heat transfer measurements are taken in the experiments. Unsteady passing shock is generated in a shock tube and introduced into the test section of the cascade to simulate the shock wave passage similar to an actual turbine environment.

The research will allow determination of the magnitude of heat flux increase due to shock passing, and will provide further insight as to how shock wave in a highly loaded transonic turbine blade may adversely affect the heat transfer.

II. Progress

The heated transonic turbine cascade tunnel was thoroughly checked out and shown to have good flow characteristics. A single passing shock, generated from a shock tube, was successfully introduced into the test section. A new generation of high-response heat flux gauge was used in the experiment to document the passage of the shock in the blades, as well as the reflection of the shock and its interaction with the boundary layer. Additional measurements included high frequency Kulite pressure transducers, shadowgraphs and hot-wire sensors. A comprehensive flow picture with focus on the influence of the shock wave on the local heat transfer rate is being developed.

III. Results

A shock wave is generated from a shock tube and is introduced into the test section of the cascade. The specific goal of this experiment is to track the shock movement and correlate with peaks in heat flux and pressure using flow shadowgraphs. This will allow the determination of heat flux increase due to different orientation and strength of the shock passing. The series of shadowgraphs were used to monitor the shock progression, as shown in Fig. 1. Based on this shock progress sequence, a videotape was made to aid in visualizing the process. Four heat flux microsensors (HFM) and four Kulite high frequency pressure transducers were used in one blade passage to capture the shock motion. The locations of these sensors were shown in Fig. 1. Measurements obtained from the HFM and the Kulites were shown in Fig. 2 and Fig. 3, respectively.

Work is continuing to track the shock movement and correlate that with peaks in heat flux and pressure measured on the blade surface. A numerical model is being developed to calculate the effect of moving shock on the boundary layer heat transfer.

IV. Transitions

<u>Vatell Corp</u>

As part of the Virginia Tech research project from AFOSR, Vatell Corporation has sputtered thin-film Heat Flux Microsensors directly into the anodized surface of aluminum gas turbine blade models. With a thickness less than 2μm, these sensors offer negligible disruption of the fluid flow or heat transfer. The sensors measure both heat flux and temperature at the blade surface.

Heat flux is measured using the output of 100 nickel-nichrome thermocouple pairs arranged as a differential thermopile across a thin thermal resistance layer. The voltage output is directly proportional to the heat flux and has a flat frequency response from dc to above 100 kHz. Surface temperature is measured with an adjacent thin-film resistance element.

The development of the Heat Flux Microsensor has been a six-year cooperative venture between Virginia Tech and the Vatell Corporation. This application is a major step towards the ultimate goal of

applying these sensors directly to blades in operating gas turbines. Vatell Corporation currently markets Heat Flux Microsensors produced in its new Thermateq laboratory facility in Blacksburg VA.

General Electric Aircraft Engines

Interaction with GEAE has continued with comparison of experimental results in the cascade facility at Virginia Tech with the GEAE predicted turbine blade performance. Two important characteristics that have been measured are the loss coefficients and heat transfer coefficients under transonic conditions as experienced in engines. Heat transfer coefficients match well under low turbulence conditions. Work is continuing to compare more realistic higher turbulence conditions.

An additional reason for the industry interest is the performance of the heat flux instrumentation, which has potential application in rotating test rigs and eventually in actual engines, GEAE would like to build confidence in the instrumentation in our stationary cascade for use in these more demanding tests.

Part of the concern with any heat flux instrumentation is the lack of appropriate calibration standards for heat flux sensors. T. E. Diller of Virginia Tech is spearheading a national effort to work with NIST to establish standards for convective heat flux.

V. Personnel

Principal Investigators: Wing Ng and Tom Diller

Graduate Students (all are US citizens):

Name	Degree	Source of Funding
Missy Fasold	MS	AFOSR
Jamie Hale	MS (completed 4/96)	AFOSR
Dave Holmberg	PhD	Air Force Fellowship
Drew Nix	MS	ASSERT
Terry Reid	PhD	NASA Fellowship
Angela Wesner	PhD	NSF Fellowship

VI. Publications

Book Chapters

Diller, T. E., and Tien, C. L., "Temperature and Heat Flux Measurement," Ch. 15.10 in Handbook of Fluid Dynamics & Fluid Machinery, Vol. 2, Eds. J. A. Schetz and A. E. Fuhs, John Wiley & Sons, N. Y., 1996, pp. 1053-1064.

Refereed Journal Publications

Holmberg, D. G. and Diller, T. E., "High-Frequency Heat Flux Sensor Calibration and Modeling," **ASME Journal of Fluids Engineering,** Vol. 117, 1995, pp.659-664.

Refereed Conference Publications (Full Paper Review)

Diller, T. E., "Methods of Determining Heat Flux From Temperature Measurements," in Proceedings of the 42nd International Instrumentation Symposium, ISA, Research Triangle Park, N. C., 1996, pp. 251-262.

Yang, T. T. and Diller, T. E., "Heat Transfer and Flow for a Grooved Turbine Blade Tip in a Transonic Cascade," ASME Paper 95-WA/HT-29, 1995.

Holmberg, D. G. and Pestian, D. J., "Wall-Jet Turbulent Boundary Layer Heat Flux, Velocity, and Temperature Spectra and Time Scales," ASME Paper 96-GT-529, 1996.

Reid, T. V., Ng, W. F. and Lucci, B. L., "Effects of Wake Passing on the Unsteady Heat Transfer on a Turbine Cascade," AIAA Paper 96-2789 for the AIAA 32nd Joint Propulsion Conference, Lake Buena Vista FL, 1996.

Publications Submitted

Reid, T. V., Nix, A. C., Ng, W. F., Diller, T. E. and Schetz, J. A., "Unsteady Surface Heat Transfer on a Transonic Turbine Blade due to Shock Wave Passing," accepted for publication for the AIAA Aerospace Sciences Meeting, Reno NV, 1997.

Diller, T. E., Ng, W. F. and Schetz, J. A., "Time-Resolved Measurements of Turbine Blade Flow Phenomenon," submitted for AGARG meeting, 1997.

Holmberg, D. G., Diller, T. E. and Ng, W. F., "Role of Turbulence Scales on Mean and Time-Resolved Heat Transfer in a Transonic Turbine Cascade," submitted for the IGTI Conference, Orlando FL, June 1997.

Hale, J. H., Diller, T. E. and Ng, W. F., "Effects of a Stationary Wake on the Heat Transfer in a Transonic Turbine Cascade," submitted for the IGTI Conference, Orlando FL, June 1997.

VII. Patents

Diller, T. E., and Onishi, S., "Heat Flux Gage," European Patent Publication No. 0349618B1, May 7, 1995.

VIII. Awards (new for 1995-96)

Wing Ng
- Elected ASME Fellow, 1996
- Japanese Government Research Awards for Foreign Specialists to lecture in Japan, 1996
- Certificate of Recognition from NASA for contributions to the Supersonic Throughflow Technology Team, 1995

Tom Diller
- Who's Who in the South and Southwest, 24th ed., 1995
- Who's Who in the World, 12th ed., 1995
- Who's Who in Science and Technology, 3rd ed., 1996
- Chairman of the Ad-hoc Committee on Heat Flux Calibration and Standards of the ASME Heat Transfer Division, 1995-
- Who's Who in the South and Southwest, 25th Ed., 1997

Fig. 1 - Shock Progression

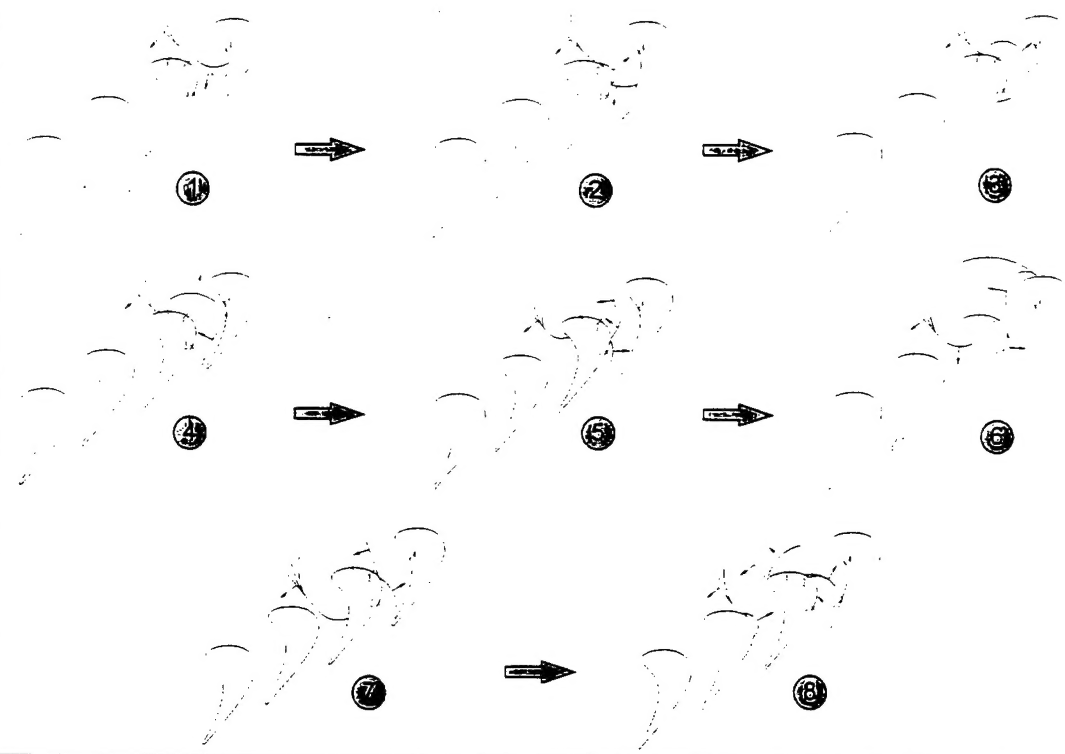

Fig. 2 - Pressure and Heat Flux Measurements